Polyethylene and Hydrogen Peroxide Hybrid Testing at the United States Air Force Academy

Captain Michael Bettner, Assistant Professor
Dr Ronald W. Humble, Visiting Professor

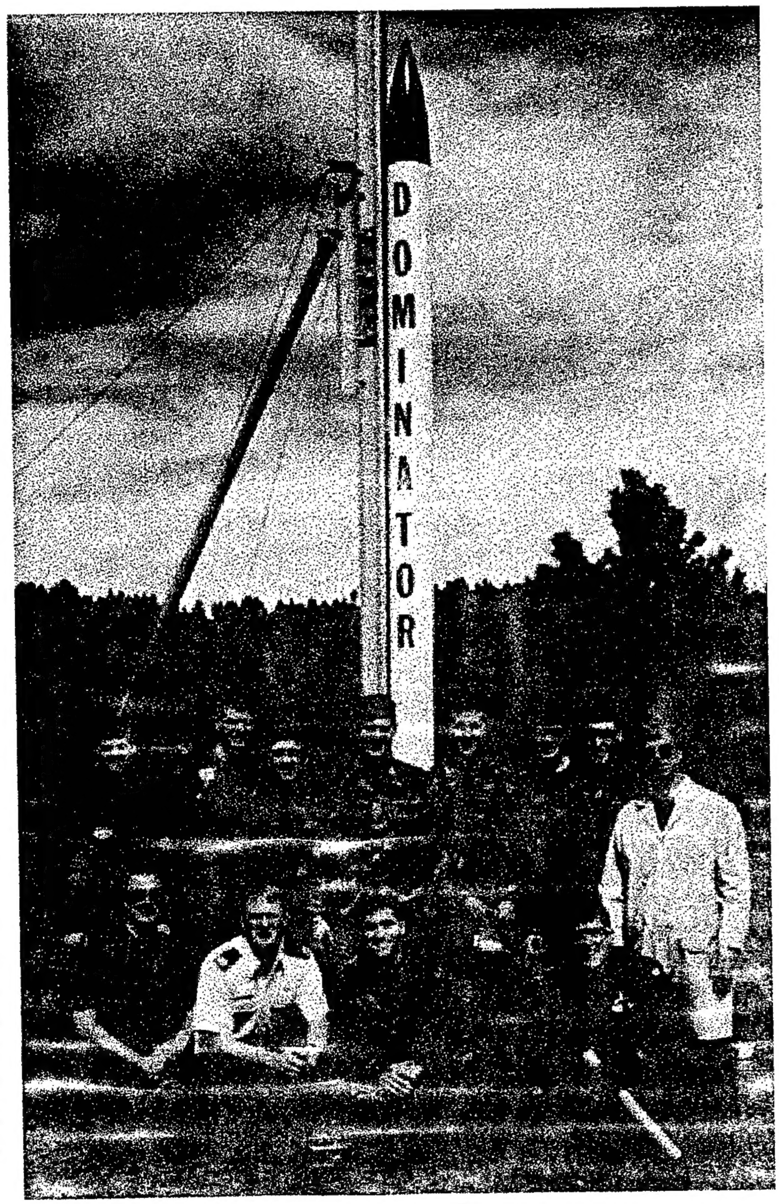
United States Air Force Academy
Department of Astronautics
2354 Fairchild Dr, Suite 6J67
USAF Academy, CO 80840-6224, 719-333-4110

ABSTRACT

The United States Air Force Academy (USAFA) has been conducting propulsion research over the past several years and has recently been focusing on hydrogen peroxide applications. A hybrid motor configuration using hydrogen peroxide as the oxidizer and polyethylene as the fuel was first tested at USAFA in the spring of 1996. While the propellants have not changed since the first test firing, significant advancements have been made in catalyst design, ignition, nozzles, and thrust levels.

Three static tests and one sounding rocket flight were accomplished during the spring semester 1998 at USAFA. The static test goals were: 1) Demonstrate autoignition of single and multiple port motors; 2) Examine methods for reducing ignition time; 3) Characterize fuel regression; 4) Gather data on flux rates through the catalyst material and fuel port; 5) Characterize and validate performance accurately through simulation; and 6) Develop sufficient thrust for a sounding rocket.

The single port motors reached a thrust level of 160 lb with ignition as fast as 0.75 sec. A four port motor reached 200 lb of thrust, ignition in 0.83 sec, and no significant nozzle throat erosion after a 15 second test firing. Results from the tests show good potential for hydrogen peroxide hybrids as a simple, safe, and relatively inexpensive propulsion system.



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
10-08-1998	Final Report	2-08-1997 to 20-05-1998

4. TITLE AND SUBTITLE
Polyethylene and Hydrogen Peroxide Hybrid Testing
At the United States Air Force Academy

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bettner, Michael
Humble, Ronald W.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
United States Air Force Academy
2354 Fairchild Drive Suite 6J71
US Air Force Academy CO 80840

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
United States Air Force Academy
HQ USAFA/DFAS
2354 Fairchild Drive, Ste 6J71
USAF Academy CO 80840

10. SPONSOR/MONITOR'S ACRONYM(S)
HQ USAFA/DFAS

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES
Presented at the 1st Annual Hydrogen Peroxide Conference Held at the University of Surrey

14. ABSTRACT
The United States Air Force Academy (USAFA) has been conducting propulsion research over the past several years and has recently been focusing on hydrogen peroxide applications. A hybrid motor configuration using hydrogen peroxide as the oxidizer and polyethylene as the fuel was first tested at USAFA in the spring of 1996. While the propellants have not changed since the first test firing, significant advancements have been made in catalyst design, ignition, nozzles, and thrust levels. Three static tests and one sounding rocket flight were accomplished during the spring semester 1998 at USAFA. The static test goals were: 1) Demonstrate autoignition of single and multiple port motors; 2) Examine methods for reducing ignition time; 3) Characterize fuel regression; 4) Gather data on flux rates through the catalyst material and fuel port; 5) Characterize and validate performance accurately through simulation; and 6) Develop sufficient thrust for a sounding rocket.

15. SUBJECT TERMS
Hybrid rockets, hydrogen peroxide/polyethylene

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES:	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	U	61 10	Col Michael DeLorenzo
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED		19b. TELEPHONE NUMBER *(include area code)* (719) 333-4110

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

INTRODUCTION

The United States Air Force Academy (USAFA) has an interest in developing a rocket motor that is simple, restartable, and safe (both in the development/experimental stage and as a passenger during orbit insertion). Particularly the goal is to get a "ride" to orbit and then provide a ΔV to a secondary spacecraft after the primary payload departs the upperstage. Hybrid rockets may meet USAFA requirements since several propellant choices exist which are easy to handle. One possible choice would be H_2O_2 and polyethylene (PE). The primary reason for looking at H_2O_2 as the oxidizer choice is the possibility for autoignition allowing for multiple starts. This analysis looks at PE as the fuel choice, however we may consider polymethyl methacrylate (PMM) or HTBP (rubber) in the future. In particular, we examine regression rate data, thrust, time to autoignition, and some possibilities for future experiments.

BACKGROUND

Our first goal was to find a way to get the PE and H_2O_2 to autoignite. Several cadet projects in the past experimented with H_2O_2 monopropellant thrusters where the H_2O_2 catalytically decomposes to hot O_2 and H_2O (using ceramic pellets impregnated with MnO_2 or $KMnO_4$ provided by the China Lake Naval Air Weapons Center). The problem was getting full decomposition before leaving the catalyst bed. One possible explanation is that the high velocity stream of H_2O_2 exiting the injectors penetrates the cat bed without contacting enough surface area.

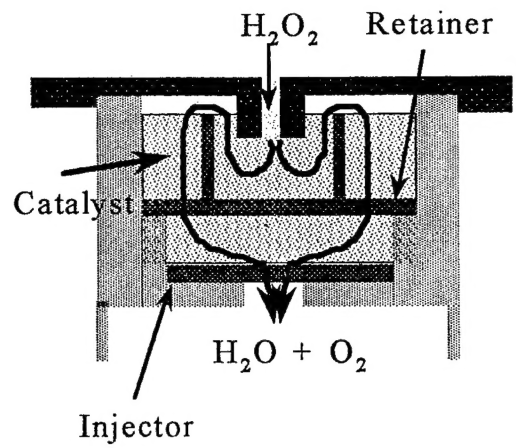


Figure 1: Ceramic pellet catalyst housed in dual-chamber design.

In figure 1, you can see our first design. This design houses two chambers for the catalyst. The catalyst was impregnated on ceramic pellets. While the linear travel distance is still about the same as earlier designs (roughly 5 cm), this design prevents the H_2O_2 stream from burrowing a path straight to the exit point. While we did have successful tests with this design, the mass flow rates were less than desired.

We abandoned this concept after successful monoprop testing using MnO_2 on a cordierite ceramic material made by Corning. This material has several hundred axial channels per square inch in a honeycomb pattern. The new material allows for axial flow, high surface area contact, and minimal pressure drop. Initial tests used a 1" diameter and 2.5" long cat bed in a monopropellant thruster that developed just under 20 Newtons of thrust. Looking at figure 2, the H_2O_2 first passes through a solid cone spray nozzle. The goal is to evenly distribute the H_2O_2 onto the catalyst since all the flow passages are axial. The H_2O_2 should decompose into water and oxygen gas at 800 - 900 K. Although the H_2O_2 did not fully decompose (there was visible steam in the exhaust), the hot gas exhaust appeared adequate to vaporize PE, allowing autoignition and combustion to occur. The monopropellant thruster simply had a converging/diverging

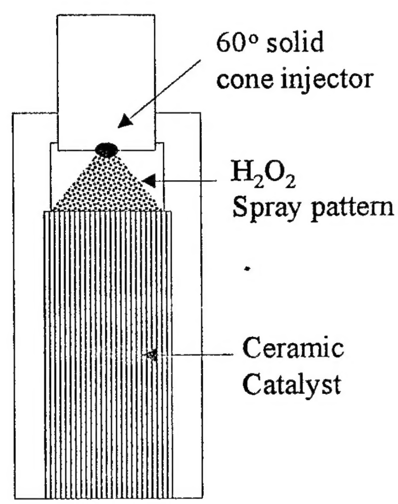


Figure 2: Axial flow catalyst design.

conical nozzle aft of the catalyst. In the hybrid motor, the hot gases flowed through PE port(s) before reaching the nozzle.

This design was successfully incorporated into a H_2O_2 /PE hybrid motor. Catalyst design issues involved length of and flux through the catalyst material, spray pattern, and preventing H_2O_2 from flowing around the ceramic (channeling).

Next a brief background on the thermochemistry involved in the hybrid. First, we use the Air Force's Isp Code to develop molecular weight (MW), chamber temperature (T_c), and isentropic parameter (gamma or γ) relationships for various oxidizer to fuel ratios (O/F). After running the Isp code, polynomials are fit to the data as shown in figures 3 and 4.

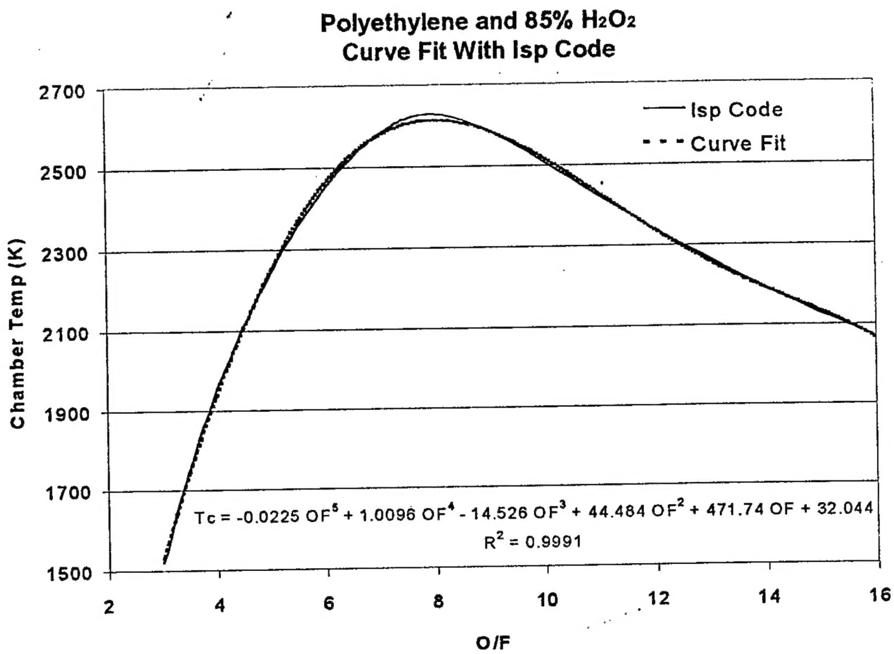


Figure 3: Chamber temperature as a function of peroxide to polyethylene mass ratio.

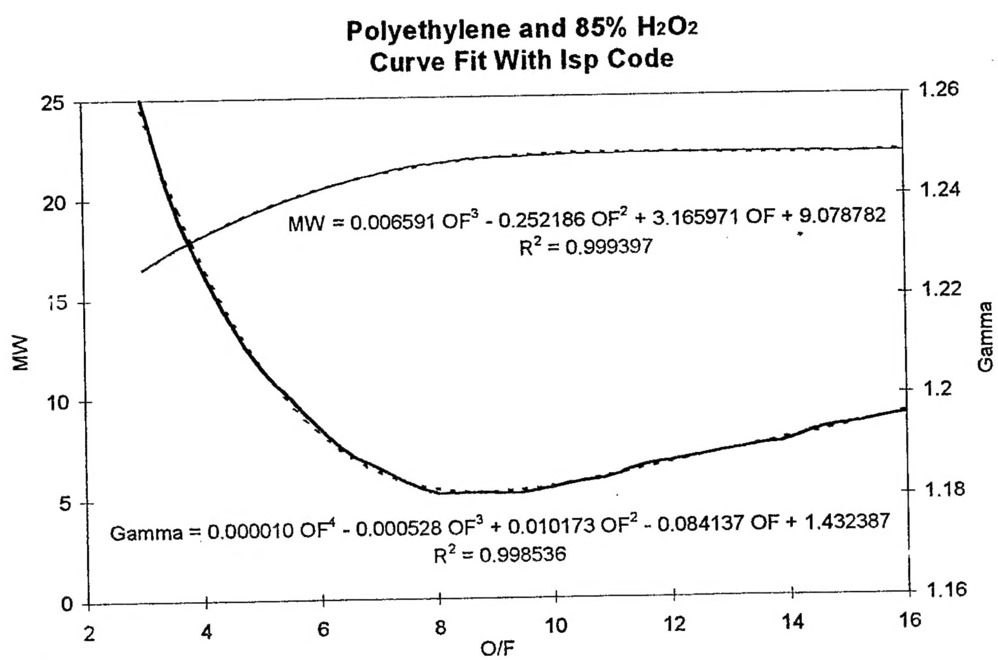


Figure 4: Chamber molecular weight (MW) and isentropic parameter (γ) as a function of peroxide to polyethylene mass ratio.

Once the chamber gas temperature, molecular weight, and gamma are known, we can find the characteristic exhaust velocity, c*, using the following relationship:

$$c^* = \frac{\sqrt{\gamma R T_c}}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \qquad \text{Equation 1}$$

Where R is the universal gas constant divided by the molecular weight of the gas. If we know the nozzle throat area (A_t) and mass flow rate we can then find the chamber pressure (P_c) using the following isentropic relationship:

$$c^* = \frac{P_c A_t}{\dot{m}} \qquad \text{Equation 2}$$

Knowing the nozzle exit area (A_e), the exit pressure (P_e) can be easily determined from isentropic relationships. This will allow us to find the coefficient of thrust, C_F, using equation 3. Finally, we can now find the specific impulse (Isp) and thrust level (F) using the following relationships (where g_o is sea level gravity):

$$C_F = \left\{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} + \frac{(P_e - P_a)A_e}{P_c A_t} \qquad \text{Equation 3}$$

$$Isp = \frac{c^* C_F}{g_o} \qquad F = Isp\, g_o \dot{m} \qquad \text{Equations 3, 4}$$

Looking at figures 3 and 4 it appears an O/F of 8 should result in the maximum Isp. Since the O/F typically increases for hybrids as the port burns, the design generally should target on O/F lower than optimum at the start and finish at a higher O/F such that the average O/F would be near 8 for our propellants. Often the differing densities of the fuel and oxidizer require adjusting the target average O/F. For example, if the oxidizer has a higher storage density than the fuel, a higher O/F may improve performance despite the lower Isp dictated by the thermochemistry.

In order to develop simulations, we must make some assumptions about the hybrid ballistics. First we assume the regression rate relationship is:

$$r = aG^n L_p^{\ m} \qquad \text{Equation 5}$$

where:

r = regression rate (m/s)
G = mass flux rate (kg/m^2s)
L_p = length of fuel port (m)
a = regression rate coefficient
m, n = regression rate exponents

Next we use values of $a = 0.000007$, $n = 0.8$ and $m = -0.2$ for PE/H_2O_2. These regression rate parameters were empirically determined from earlier PE/H_2O_2 tests. This is the where simulation is critical. First we simulate a design. After the test firing the simulation is compared to the actual results. The regression parameters are adjusted until the thrust and pressure profiles along with initial and final fuel geometry of the simulation matches the test results. Finally, we assume a nozzle efficiency of 0.95 and a c* efficiency of 0.85 (to account for combustion inefficiencies). Thus, given an oxidizer mass flow rate,

nozzle dimensions, and PE grain geometry, we can use these relationships to simulate the port regression and trust profile.

TEST SETUP

The hybrid tests used compressed nitrogen regulated at 500 psi to pressurize the oxidizer tank. An electric solenoid valve controlled the flow of the nitrogen gas into the tank holding the H_2O_2. The H_2O_2 would then flow through a spray nozzle, through the catalyst, and then into the PE port(s). A pressure transducer was located between the solenoid valve and the inlet to the oxidizer tank. The motors were fired vertically on a test stand capable of measuring up to 500 lb of thrust. The first two static tests used a single port configuration as shown in figure 5. The third test used a four port design as shown in figure 6. The four port motor had a 350 psi burst disc located between the H_2O_2 tank and spray nozzle to control starting the higher flow-rate motor.

Single Port PE/H_2O_2

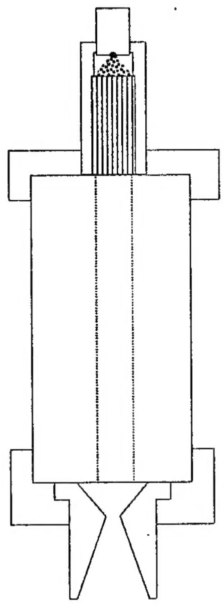


Figure 5: Single port configuration

4 Port PE/H_2O_2

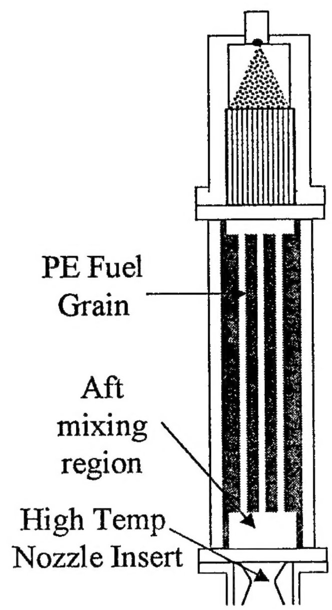


Figure 6: Four port

RESULTS

The first test motor was a 15 inch long PE grain with a 3/4" inch diameter port. This test used approximately 0.6 kg of H_2O_2. The 5/8" diameter nozzle had a PE insert to restrict the flow until ignition. This allows the H_2O_2 adequate residence time in the cat bed to sufficiently decompose. The insert would then ablate away allowing the thrust to increase. Our 20 Feb 98 test was successful and had a 3/4 sec ignition time. Prior to ignition, white steam was exiting the nozzle with no visible indications of liquid. However, the H_2O_2 ran out before the PE insert ablated away completely, thus full thrust was not developed. Expected thrust was approximately 160 lb.

The pressure plot in figure 7 contains much useful information. First we notice where the solenoid was opened - the pressure begins to increase. Next we know when the H_2O_2 supply ran out by the rapid drop of thrust and corresponding drop in nitrogen pressure. We expect this pressure drop as nitrogen flow rate increases. Additionally we can observe when the solenoid was closed because of the rapid pressure drop as nitrogen aft of the solenoid rapidly diminishes. Another interesting observation is that the thrust level begins to increase between 31 and 31.25 seconds. A possible explanation is the exhaust gases transition from a mixture of nitrogen, water, oxygen, and possibly trace amounts of peroxide to an exhaust gas of mainly nitrogen. The lower molecular weight of nitrogen results in a higher

Isp and higher thrust level. Once the solenoid valve is closed, both the pressure and thrust diminish as the nitrogen aft of the solenoid is depleted.

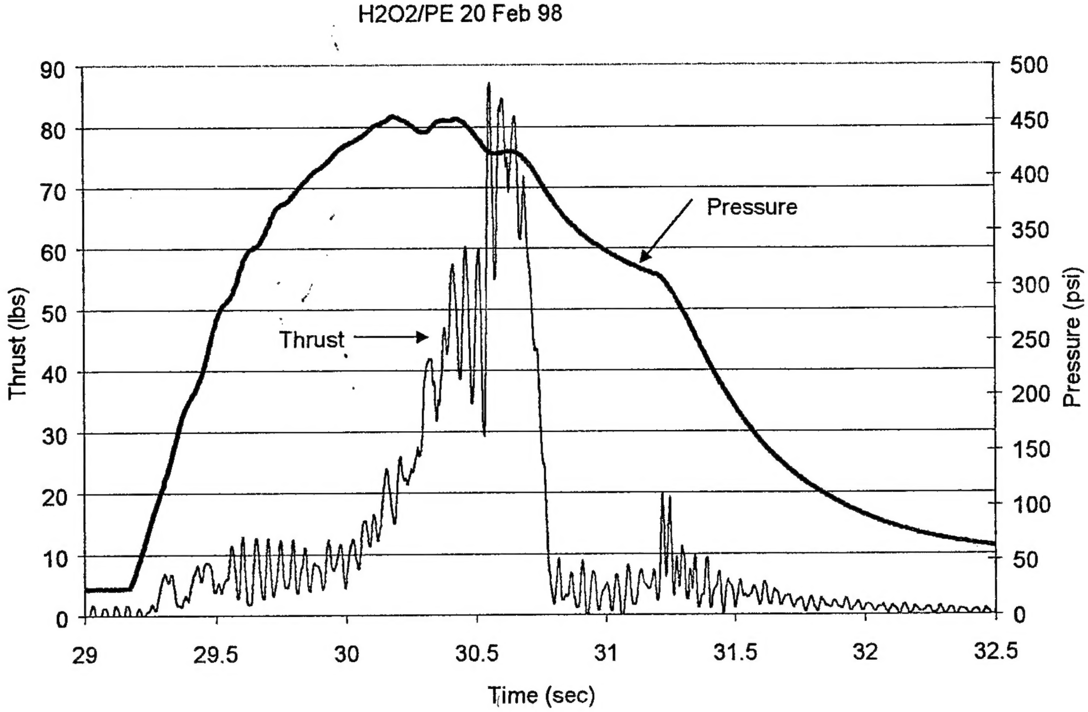


Figure 7: Single port thrust and pressure profile. Peroxide supply consumed before full thrust

Our next test was 4 Mar 98 using the same PE grain. The purpose of this test was to develop full thrust. A PE nozzle insert was used again and we increased the amount of H_2O_2. As Figure 8 shows, we successfully achieved ignition in about 0.8 sec and the thrust began to increase as expected. However, after ramping up nicely to 60 lb of thrust, what remained of the PE insert blew through the nozzle. The thrust rapidly increased. the motor began to chug, combustion in the port ceased, and then only white steam exited the nozzle until the peroxide supply diminished.

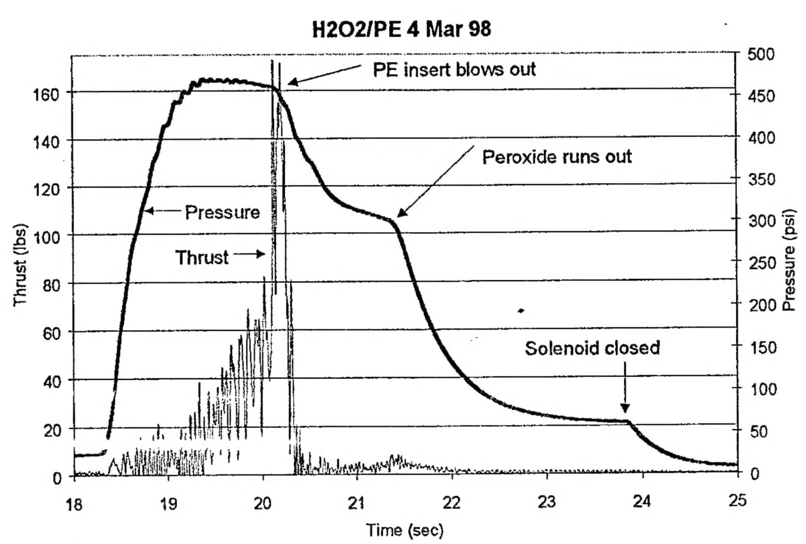


Figure 8: Single port thrust and pressure profile. Nozzle insert blew out shortly after ignition. Drastic increase in mass flow rate causes termination of combustion.

Our 4 Mar 98 test was the first test where combustion ceased post-ignition with H_2O_2 still flowing. After examining the results and running

simulations, we have a possible explanation. The PE nozzle insert was designed to ignition time and provide a gradual ramp up to maximum thrust. In effect, the PE insert acted as an ablative nozzle throat. The effective nozzle throat diameter was small initially to keep the H_2O_2 flow rate low while maintaining a reasonable chamber pressure. As the PE insert ablates away, the nozzle throat diameter increases allowing higher mass flow rates. Eventually, when the PE insert is fully consumed, the nozzle throat diameter should remain at 5/8".

Our design expected the port diameter to increase during this ramp up. As the port diameter increased, the total mass flux, G, would decrease. A rule of thumb limit on oxidizer mass flux is 350 - 700 kg/s m^2. Since we were using a hot gas oxidizer (H_2O and O_2), we targeted a G of 700. The port was sized to hit a G of 700 at the time of max thrust. However, when the insert blew out, the oxidizer mass flow rate increased while the port diameter was still too small. This caused a rapid increase in G. We expect that we exceeded the limit that could sustain combustion. This gives us a "blowoff" phenomenon similar to extinguishing a match by blowing air (oxidizer) over the flame. Figure 9 shows the oxidizer flux rate through the port and figure 10 shows the flux through the catalyst bed. The PE insert design was modified to prevent this from occurring on future tests.

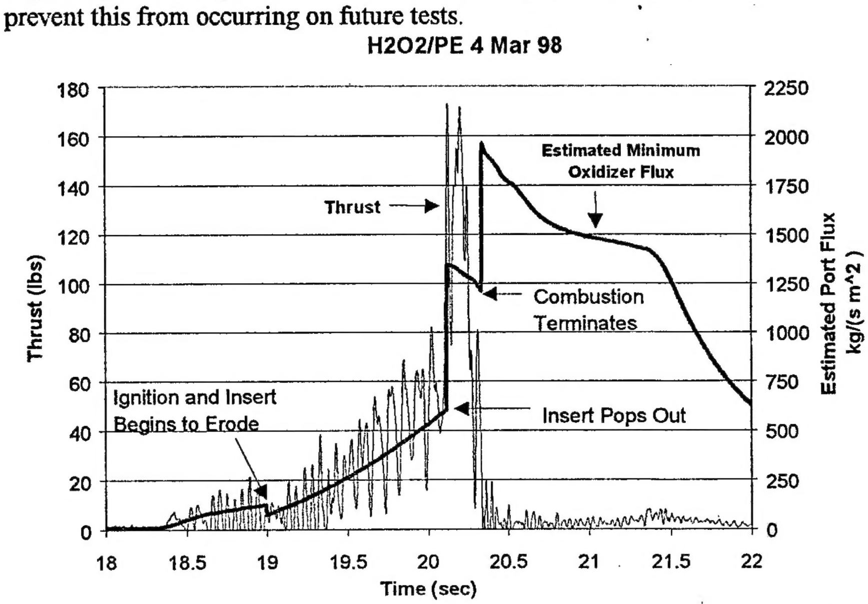


Figure 9: Combustion terminates with peroxide still flowing. Possibly caused by high oxidizer flux (greater than 700) through the port.

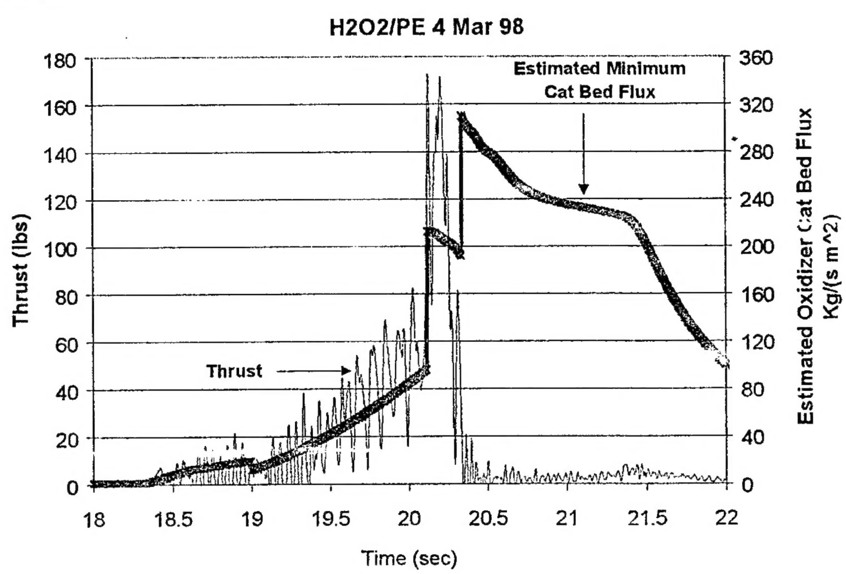


Figure 10: Visible liquid (peroxide) noticed in exhaust gases after flameout. Possibly caused by high (above 250) oxidizer flux rate through the cat bed.

The flux plots in figures 9 and 10 are estimates only. Since we did not have mass flow data directly, this information had to be backed out from thrust and pressure data. This was calculated assuming a port diameter of 3/4", a catalyst diameter of 1" and then using the isentropic relationship in equation 2. We assumed a c* of 900 m/s for decomposed H_2O_2 with no PE burning and a c* of 1300 m/s for H_2O_2/PE combustion. The nozzle throat diameter started at 5/32" (the initial diameter of the PE insert) and was increased at an assumed rate of 3 mm/s after ignition until the insert popped out. The nozzle diameter was then held constant at 5/8". These assumptions allow us to estimate the throat area during the test since we had chamber pressure data. The value of 3 mm/s was arrived at by iterating until the simulated thrust level reasonably matched the actual thrust data.

With pressure, throat area, and c* we can back out a minimum mass flow rate. Pre-ignition and post-flame-out we treated the motor as a monoprop, thus the mass flow rate was the mass flow rate of the oxidizer. For the hybrid portion, we had to make an additional assumption that the average O/F was 8. This allowed us to calculate oxidizer mass flow rate from the total mass flow rate. To get the flux rate, simply divide the mass flow rate by the cross sectional area of the catalyst or the port as desired.

We can be fairly confident we exceeded a flux rate in the port of 1200! This seems to support the rule of thumb presented earlier. The catalyst flux is also of interest. A "rule of thumb" mass flux for peroxide cat beds is 250 kg/m^{2}sec. We can see we may have exceeded this value as well after flameout. This may explain why there appeared to be some liquid in the exhaust after flameout but before the peroxide supply was exhausted.

Our next goal was to develop a 500 lb thrust motor to fly on a cadet built sounding rocket. The design utilized a four port PE grain. Each port had a circular 7/8" diameter port. The grain was 18" long with a forward and aft mixing region (effective length of 16.5"). The nozzle had a 1" diameter throat and an expansion ratio of 6.8. Since we had not yet determined the flux rate limit on the catalyst (the maximum before washout or incomplete decomposition), we used a 4" diameter and 3" long catalyst for the new motor. The cordierite material had 800 pores rep square inch. We scaled our catalyst such that the increased mass flow rate would not exceed the G value from previous tests. The motor was test fired with 6 kg of peroxide. Once the peroxide flow started, white steam was observed exiting the nozzle as shown in figure 11. Ignition occurred approximately 0.83 seconds later and the steam disappeared as full thrust developed (see figure 12). The thrust and pressure profile is shown in figure 13.

14 April 98 Four Port H_2O_2/Polyethylene Hybrid Static Test

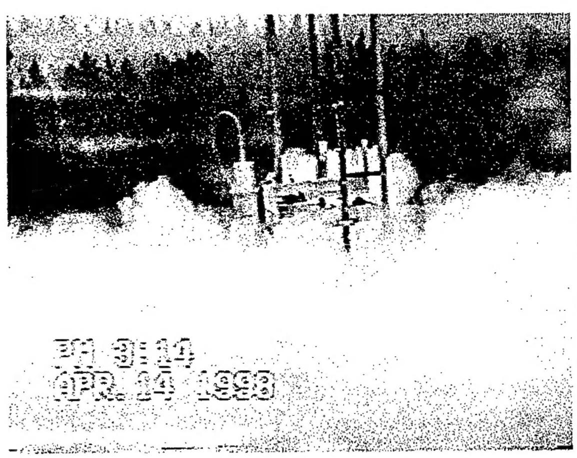


Figure 11: Peroxide flow started but prior to autoignition. White steam indicates peroxide not fully decomposed.

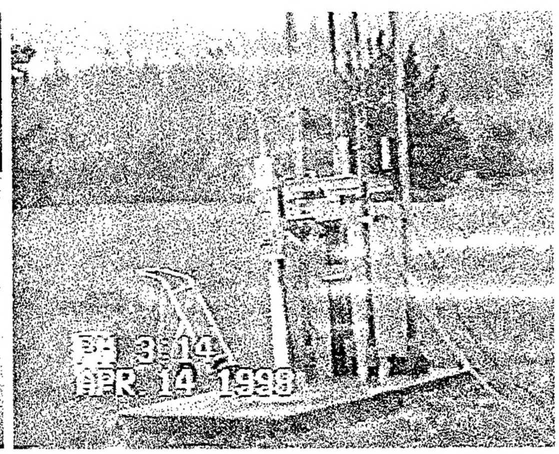


Figure 12: Post-ignition with full thrust developed.

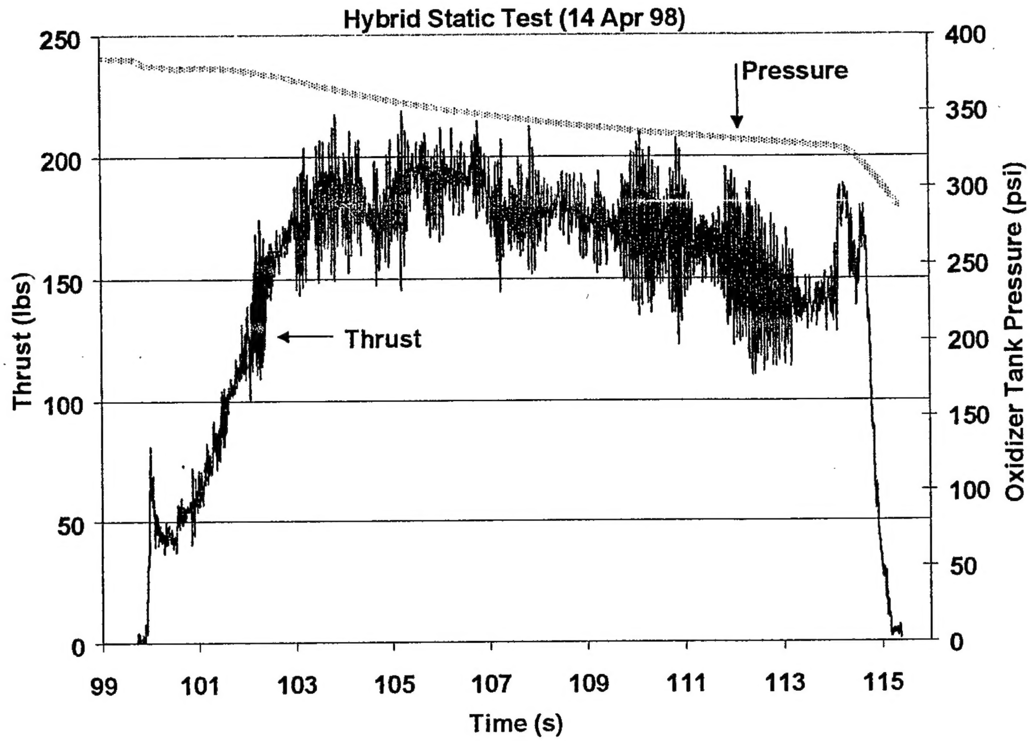


Figure 13: Four port peroxide/polyethylene hybrid thrust and pressure profile. Notice thrust ramp up as polyethylene nozzle insert ablates away.

A simulation was generated using the regression law stated earlier with a=0.000007, n=0.8, and m= -0.2. The simulation allows the peroxide mass flow rate to vary with nozzle throat diameter. Additionally we used a c* efficiency of 0.86 (frozen flow) and nozzle efficiency of 0.95. These parameters resulted in a reasonable match between the simulation and experimental data and a comparison is shown in figure 14.

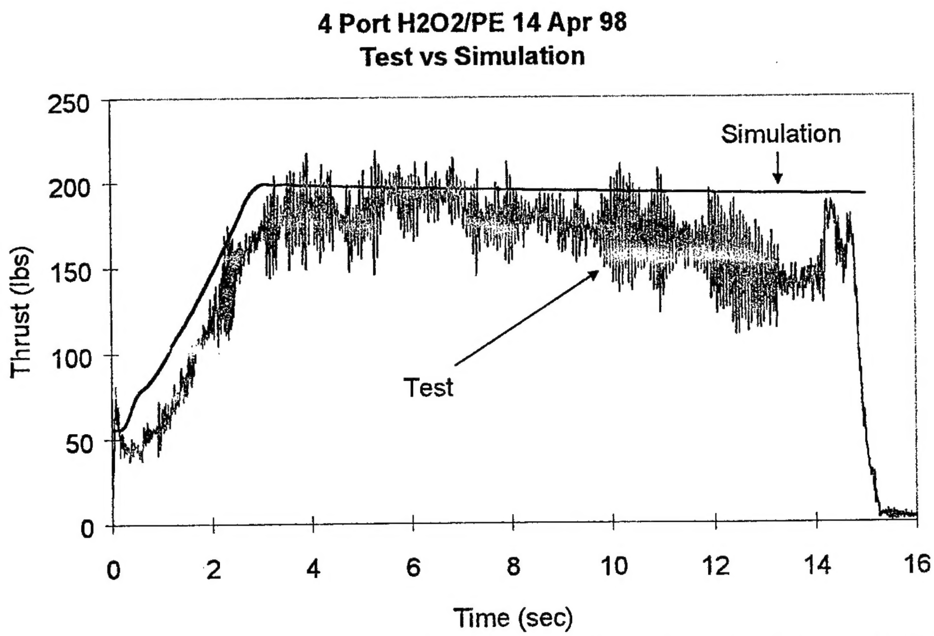


Figure 14: Simulation with a=0.000007, n=0.8, and m= -0.2, c* efficiency 0.86 (frozen flow) and nozzle efficiency of 0.95.

The oxidizer tank pressures were less than expected (the motor design expected a 500 psi tank pressure). We later discovered during a water test that pressurant flow through the solenoid valve was overly restricted. We could not get pressurant into the oxidizer tank fast enough to support the desired H_2O_2 mass flow rate of approximately 1 kg/s.

The presence of white steam in the exhaust as shown in figure 11 was also a surprise. We expected the 4 inch diameter by 3 inch long catalyst be more than adequate to ensure complete decomposition of the peroxide. Examination of the cordierite material after the test indicated the MnO_2 was only absorbed 0.5 inches from each end. It would appear we only had an effective cat bed length of 1 inch! Although the presence of white steam indicated incomplete decomposition, the temperature of the water, oxygen, and hydrogen peroxide leaving the cat bed was adequate to achieve ignition in 0.83 seconds.

Despite these shortcomings, there were many successes here. First, the nozzle insert was made of a proprietary material capable of sustaining high temperatures for several minutes. The nozzle diameter showed no signs of enlarging during the 15 second burn. The same material was used on a sounding rocket which burned for approximately 25 seconds with similar results. Secondly, all four ports lit and burned in a similar fashion. This was our first multi-port peroxide motor and no significant design changes were required. Ignition and regression compared nicely with earlier single-port designs. Lastly, the PE insert kept ignition time low (0.83 sec). Earlier tests without nozzle inserts had ignition times as high as 2 1/2 seconds. The PE nozzle insert also provided an additional benefit. The insert was designed in such a way that it provided ablative cooling for the motor's aft end. Since the motor case was made of aluminum, it was important to have some method of thermal protection.

With the end of the semester rapidly approaching, we decided to fly this motor at its current thrust level. The motor powered a cadet built 17 foot long rocket weighing 150 lb on 3 May 98. Since the vehicle was overweight and the motor was short on thrust, the launch was augmented with two 250 lb solid motors. We wanted an initial thrust/weight ratio of 5 to get the rocket off the launch rail with enough velocity for stable flight. The solids were ignited after the first sign of white steam from the hybrid. Unfortunately only one solid lit. The asymmetric thrust resulted in the rocket pitching over about 20 degrees before the hybrid developed full thrust. Since the hybrid was still thrusting at apogee, the parachutes were ripped from the rocket. It impacted the ground approximately 25 sec after launch still at full thrust!

CONCLUSION

Our tests show that H_2O_2 and the MnO_2 impregnated ceramic catalyst has enormous potential for both monoprop thrusters and high thrust hybrids. We made little if any attempt to optimize performance on the tests discussed. Most of our test firings were proof on concept, ultimately leading to a student built hybrid motor and sounding rocket. Future tests could include finding mass flux rate limits of the catalyst, examining starting and restarting capability without nozzle inserts, and using other fuels (HTPB perhaps). We have also found this technology to be suitable for undergraduate students. With proper supervision the motors are easy to make and safe to handle.

Figure 15: 3 May 98 launch of four port polyethylene/peroxide hybrid sounding rocket (17 feet long and 150 lb).